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A self-consistent approach for the determination of Schottky barrier height from reverse (*I–V*) characteristics

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Abstract : A self-consistent approach based on a curve fitting technique for the determination of Schottky barrier height from revrse (*I–V*) characteristics has been developed The technique is very suitable for such cases where the conventional (*I–V*) method for determining the barrier height becomes impractical due to the nonlinearities in the forward (*I–V*) characteristics. The validity of the technique has been checked by processing the experimental data of (*I–V*) measurements of Ni/n-Si (111) MIS Schottky diodes

Keywords : Schottky barrier height, (*I–V*) characteristics, self-consistent approach

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1. Introduction

The barrier height is an important parameter of a Schottky diode. which controls the electrical conduction through it. The conventional (*I–V*) method for determining this parameter is to plot the logarthmic value of the current density as a function of voltage. The intercept of this plot on the current axis yields the saturation current density from which the barrier height is extracted [1,2].

But, this method fails to give reliable results in case of nonideal (*I–V*) characteristics which is a common feature of practical Schottky diodes [3–6]. In such cases, a curve-fitting technique is a suitable method for processing the experimental data. In view of the above fact, a self-consistent approach based on a curve-fitting technique for the determination of Schottky barrier height from reverse (*I–V*) characteristics has been developed and is

This paper has been presented in PHOTONICS–98 : International Conference on Fibre Optics & Photonics held at Indian Institute of Technology, Delhi, India (December 14–18, 1998) reported in this paper. The technique is based on the quadratic dependence of the barrier height upon reverse-bias voltage, and does not involve any iterative procedure that is inherent in the least-square methods applied to the nonlinear systems.

2. Our approach

Generally, most practical Schottky diodes are not ideal but are instead, metal-thin interfacial layer-semiconductor (MIS) structure due to the inadvertent presence of a thin interfacial layer produced during processing. Such inadvertent interfacial layers can arise due to oxide layers, chemical reactions, cross-diffusion *etc.*

According to thermionic-diffusion theory based on MIS structure model developed by Wu [7], the majority carrier (electron, in this case) current density under nonequilibrium conditions is given by

$$J_f = \frac{A^{**}T^2}{1 + \theta_n v_R / v_D} \exp\left(-q\phi_{bf}/kT\right)\left[\exp\left(qV_f/kT\right) - 1\right], \tag{1}$$

where $$\phi_{bf} = \phi_{bo} + V_{if}. \tag{1a}$$

Here ϕ_{bo} is the zero-bias barrier height of the diode; V_{if} is the voltage drop across the interfacial layer at forward bias voltage V_f; A^{**} is the effective Richardson constant including the transmission probability across the interfacial layer; θ_n is the transmission coefficient of electrons across the interfacial layer; v_R is the thermal velocity of electrons; v_D is the effective diffusion velocity of electrons in the semiconductor depletion region. Other symbols have their usual significance.

For high mobility semiconductors (like Ge, Si, GaAs *etc*), $v_D \gg v_R$ and so the eq. (1) may be reduced to

$$J_f = A^{**}T^2 \exp\left(-q\phi_{bf}/kT\right)\left[\exp\left(qV_f/kT\right) - 1\right]. \tag{2}$$

Under reverse-bias voltage V_r (much greater than kT/q), the majority carrier (electron) current density is given by

$$J_r = A^{**}T^2 \exp\left(-q\phi_{br}/kT\right), \tag{3}$$

where $$\phi_{br} = \phi_{bo} - V_{ir}, \tag{3a}$$

V_{ir} being the voltage drop across the interfacial layer at reverse bias voltage V_r.

Using the fact that the net charge trapped in the interface states remains unchanged under most ranges of the reverse-bias [8], the voltage drop across the interfacial layer at reverse-bias voltage V_r can be written as

$$V_{ir} = \frac{\Delta Q_{SC}(V_r)}{C_i}, \tag{4}$$

where C_i is the interfacial layer capacitance per unit area; $\Delta Q_{SC}(V_r)$ is the charge density deviation in the space charge region at reverse bias voltage V_r with respect to zero bias.

Writing the expression for $\Delta Q_{SC}(V_r)$ in eq. (4), we have

$$V_i = \frac{\sqrt{2q\,\epsilon_s N_d}}{C_i}\left[\left(\phi_{br} - V_n + V_r - kT/q\right)^{1/2} - \left(\phi_{bo} - V_n - kT/q\right)^{1/2}\right], \tag{5}$$

where N_d is the donor concentration; ϵ_s is the dielectric constant of the semiconductor; V_n is the depth of the Fermi level below the conduction band edge in the bulk semiconductor.

Combining eqs. (3a) and (5), we have

$$\phi_{br} = \phi_{bo} - \frac{\sqrt{2q\,\epsilon_s N_d}}{C_i}\left[\left(\phi_{br} - V_n + V_r - kT/q\right)^{1/2} - \left(\phi_{bo} - V_n - kT/q\right)^{1/2}\right]. \tag{6}$$

Using data linearization technique [9] the eq. (6) can be reduced to linear system as

$$V_r = \alpha\phi_{br}^2 + \beta\phi_{br} + \gamma, \tag{7}$$

where
$$\alpha = \frac{C_i^2}{2q\,\epsilon_s N_d} \tag{7a}$$

$$\beta = -\frac{C_i^2}{q\,\epsilon_s N_d}\;\phi_{bo} + \frac{\sqrt{2q\,\epsilon_s N_d}}{}\;\phi_{bo} - V_n - kT/q)^{1/2}\,\Big| - 1, \tag{7b}$$

$$\gamma = \frac{C_i^2}{2q\,\epsilon_s N_d}\;\phi_{bo} + \frac{\sqrt{2q\,\epsilon_s N_d}}{C_i}\left(\phi_{bo} - V_n - kT/q\right)^{1/2}\Big| + V_n + kT/q. \tag{7c}$$

Now, by applying the least square curve fitting procedure to eq. (7), we get

$$\beta = \frac{x_3x_4 - x_1x_6}{x_2x_4 - x_1x_5}. \tag{8a}$$

$$\alpha = \frac{1}{x_4}\left(x_3 - \beta x_2\right), \tag{8b}$$

$$\gamma = \frac{1}{N}\sum (V_r)_N - \alpha\sum\left(\phi_{br}^2\right)_N - \beta\sum_N (\phi_{br})_N \tag{8c}$$

where
$$x_1 = \sum_N\left(\phi_{br}^4\right)_N - \frac{1}{N}\sum_N\left(\phi_{br}^2\right)_N,$$

$$x_2 = \sum_N\left(\phi_{br}^3\right)_N - \frac{1}{N}\sum_N(\phi_{br})_N\cdot\sum_N\left(\phi_{br}^3\right)_N,$$

$$x_3 = \sum_N\left(\phi_{br}^2V_r\right)_N - \frac{1}{N}\sum_N\left(\phi_{br}^2\right)_N\cdot\sum_N (V_r)_N,$$

$$x_4 = \sum\left(\phi_{br}^3\right)_N - \frac{1}{N}\sum_N(\phi_{br})_N\cdot\sum_N\left(\phi_{br}^2\right)_N,$$

$$x_5 = \sum_N \left(\phi_{br}{}^2\right)_N - \frac{1}{N}\left(\sum_N (\phi_{br})_N\right)^2,$$

$$x_6 = \sum_N (\phi_{br}V_r)_N - \frac{1}{N}\sum_N (\phi_{br})_N \cdot \sum_N (V_r)_N,$$

N being the number of sets of experimental data on $(I–V)$ measurements.

After obtaining the values of α, β and γ, one can determine the values of ϕ_{bo} and C_t with the help of eqs. 7 (a–c).

3. Discussion

To check the validity of the proposed method, the experimental data of $(I–V)$ characteristics of Ni/n-Si (111) MIS Schottky diodes fabricated by the vacuum vapour deposition of nickel on an n-type <111> oriented silicon wafer at $\sim 10^{-5}$ torr pressure has been processed. Details of the fabrication technique and the $(I–V)$ measurements have been reported in our previous papers [10,11]. Measurements were taken on a number of diodes but the results presented here are of a typical diode whose semilogarithimic plot of forward $(I–V)$ measurements has been found to be the best linear in the voltage range 1.0–3.5 V. The $(I–V)$ characteristics of the diode is shown in Figure 1. Here, the reverse current does not show saturation and

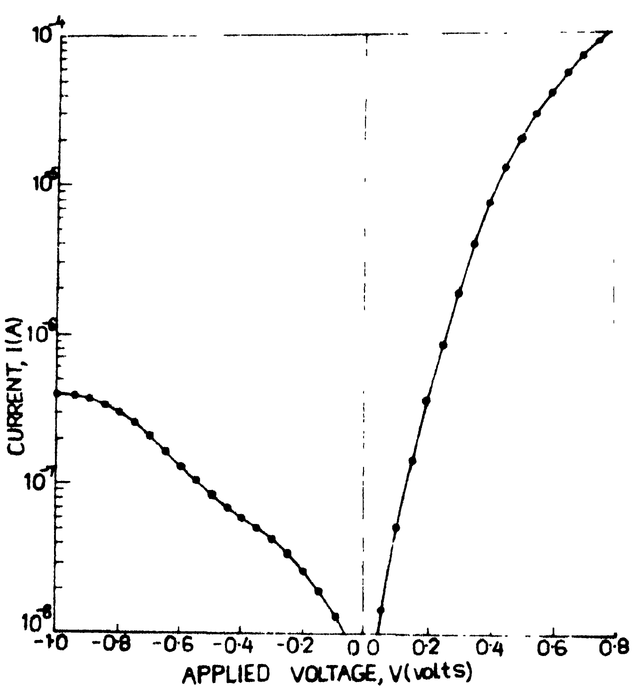

Figure 1. Measured (I–V) characteristics of a typical diode.

increases with the reverse-bias voltage. The effective donor concentration (N_d) calculated from $(C–V)$ characteristics has been found to be 1.12×10^{16} cm^{-3}. In the case of Si, near room temperature, thermionic field emission (TFE) in reversed-biased Schottky diode becomes important for $N_d > 10^{17}$ cm^{-3} while field emission (FE) may occur at moderate values of reverse-bias at higher concentrations in excess of 10^{18} cm^{-3} [2]. Thus in the diode under investigation, the obtained value of N_d rules out the TFE and the FE mechanism responsible for tunnelling of electrons through the barrier. Hence, the nonsaturation of reverse current in the diode is due to the barrier lowering.

After making the necessary correction for series resistance in the reverse (I–V) measurements, the values of barrier height ϕ_{br} have been calculated as a function of reverse-bias voltage V_r with the help of eq. (3). In this calculation, the effective Richardson constant A^{**} has been taken to be 110 A cm^{-2} K^{-2} [12]. The data ϕ_{br} *vs* V_r thus obtained, is used to get the values of α, β and γ with the help of eqs. 8 (a–c). The coefficient α then directly gives the value of C_t from eq. (7a). The zero-bias barrier height ϕ_{bo} has been determined to be 0.76 eV from eq. (7b). This value is found to be in close agreement with that calculated by the conventional (I–V) method, which supports the validity of the proposed technique. The flat band barrier height extracted from the reverse (C–V) characteristics has been found to be 0.78 eV which is greater than the zero-bias barrier height ϕ_{bo}, obviously due to the voltage drop across the interfacial layer.

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